Enabling Future Li-Ion Battery Recycling

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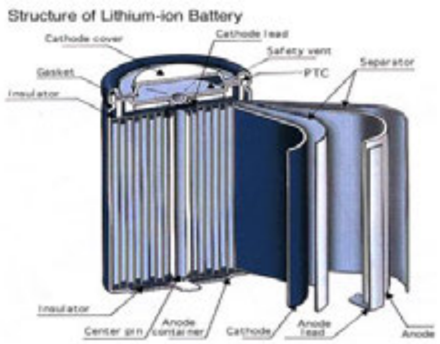
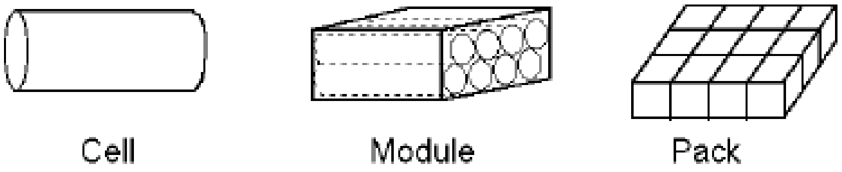
An automotive battery pack is a complex system



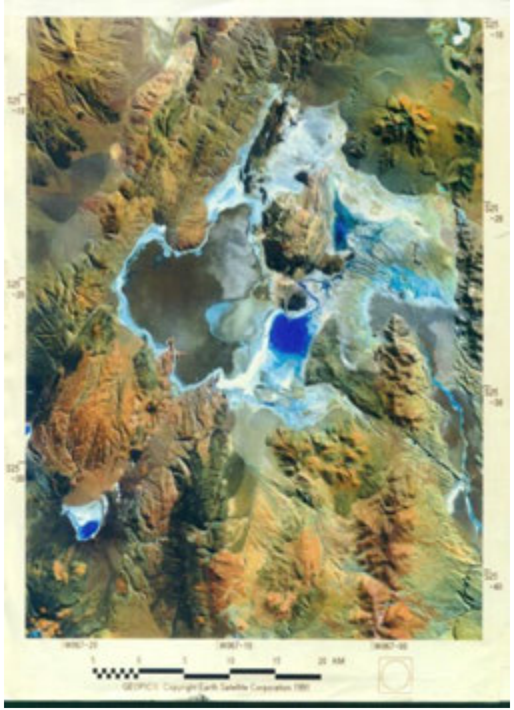


Lithium-ion cells use many materials, and cathodes vary

Cell component/ battery type	Pb-acid	Ni-MH	Li-ion
Cathode	PbO_2	$Ni(OH)_2$	LCO, NCO, LFP, or LMO
Cathode plate/foil	Pb	Ni foam	Al
Anode	Pb	MH (AB_5)	graphite
Anode plate/foil	Pb	Ni-plated steel	Cu
Electrolyte	H_2SO_4	KOH	Organic solvent + $LiPF_6$
Separator	PE or PVC w/silica	polyolefin	PE/PP
Cell case	PP	Stainless steel	Varies (metal or laminate)

LCO= lithium cobalt oxide; NCM= nickel, cobalt, manganese; LFP= lithium iron phosphate; LMO= lithium manganese oxide
PE = polyethylene; PVC = polyvinyl chloride; PP = polypropylene

Most lithium comes from salars in the Andes and is concentrated in a series of ponds



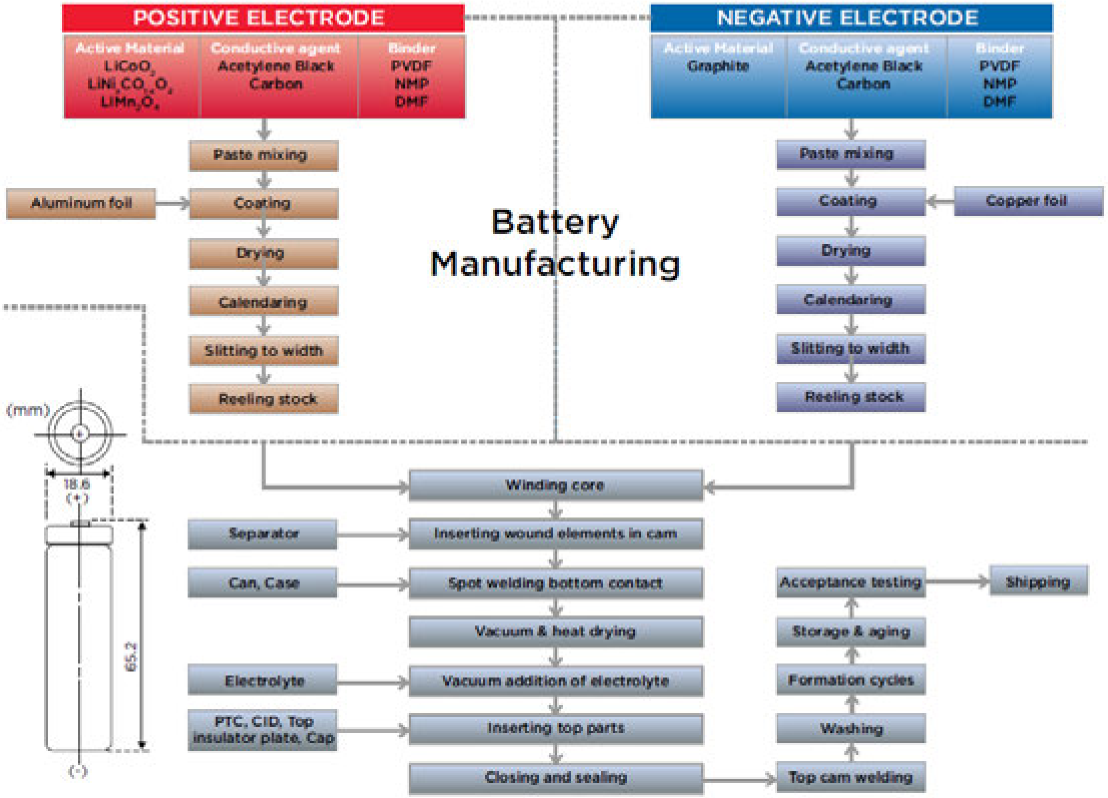
Salar del Hombre Muerto (Argentina)
[Used with permission of FMC Lithium]

Antofagasta, Chile
[Courtesy of Rockwood Lithium]

Impacts from this production are minimal

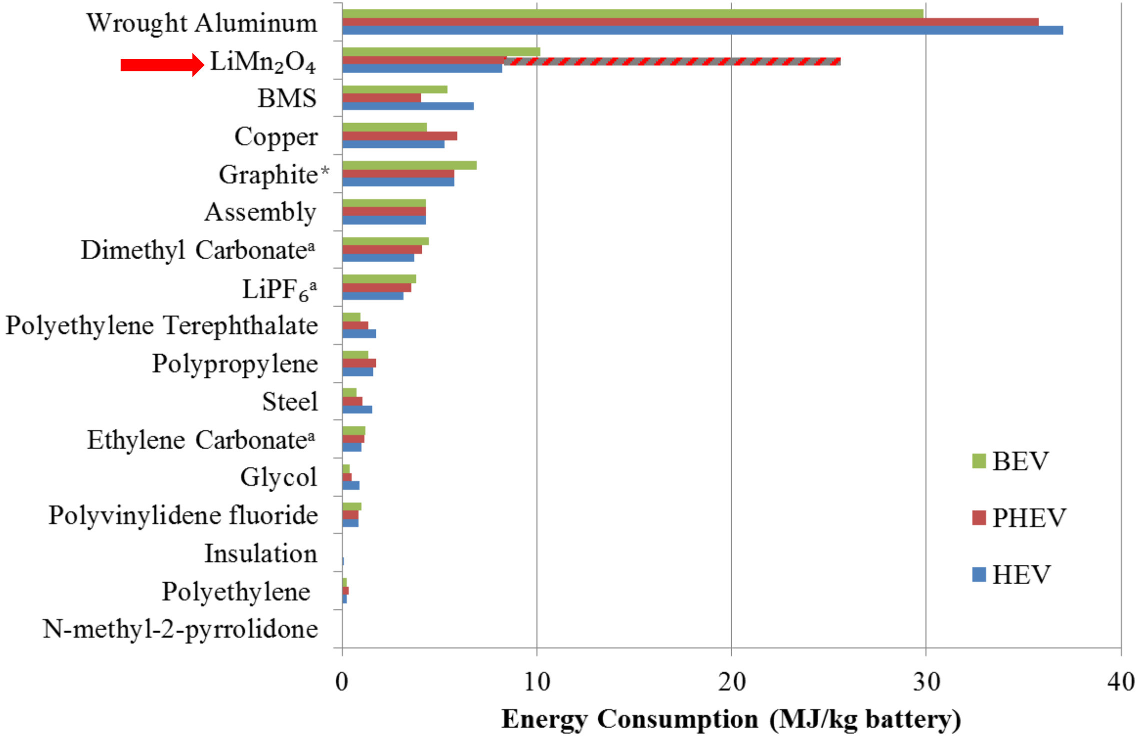
- Extraction from brine is slow, not energy-intensive
- The process energy comes primarily from sunlight
- Other salts are co-produced

Some assembly steps are performed in energy-intensive dry room



Argonne National Laboratory, Chemical Sciences and Engineering Division

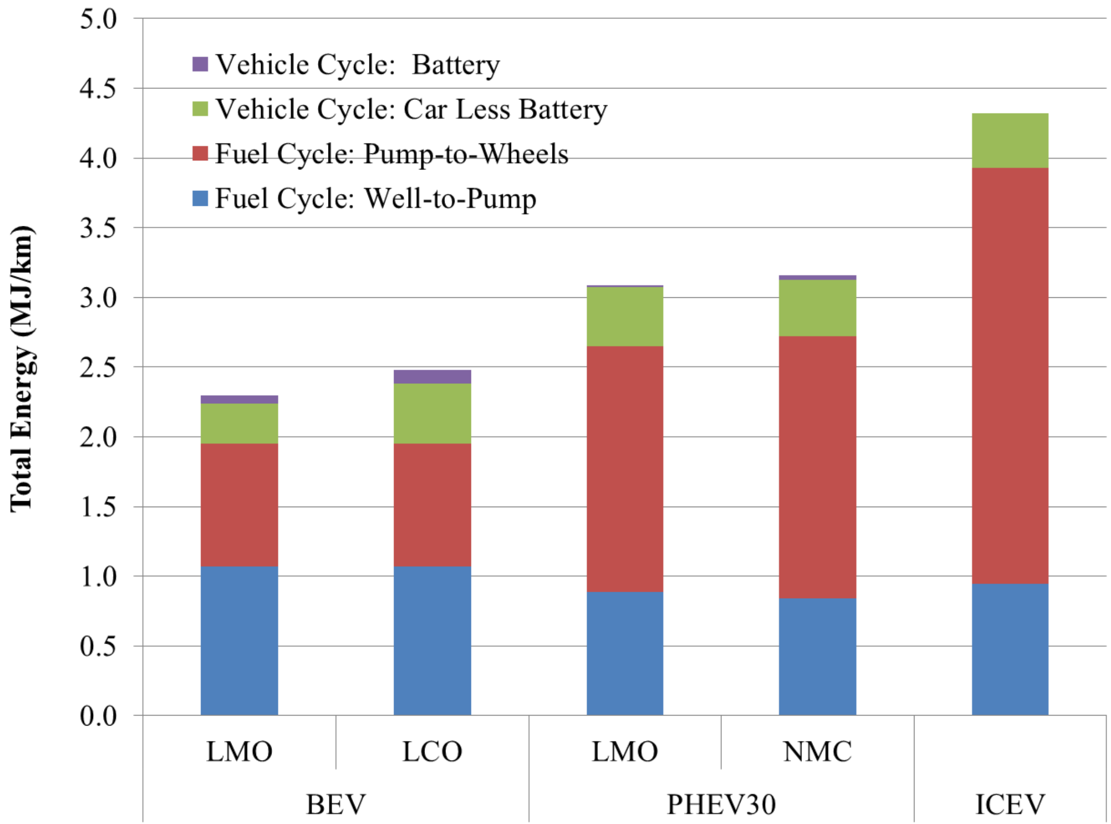
Aluminum and cathode materials dominate lithium-ion battery production energy



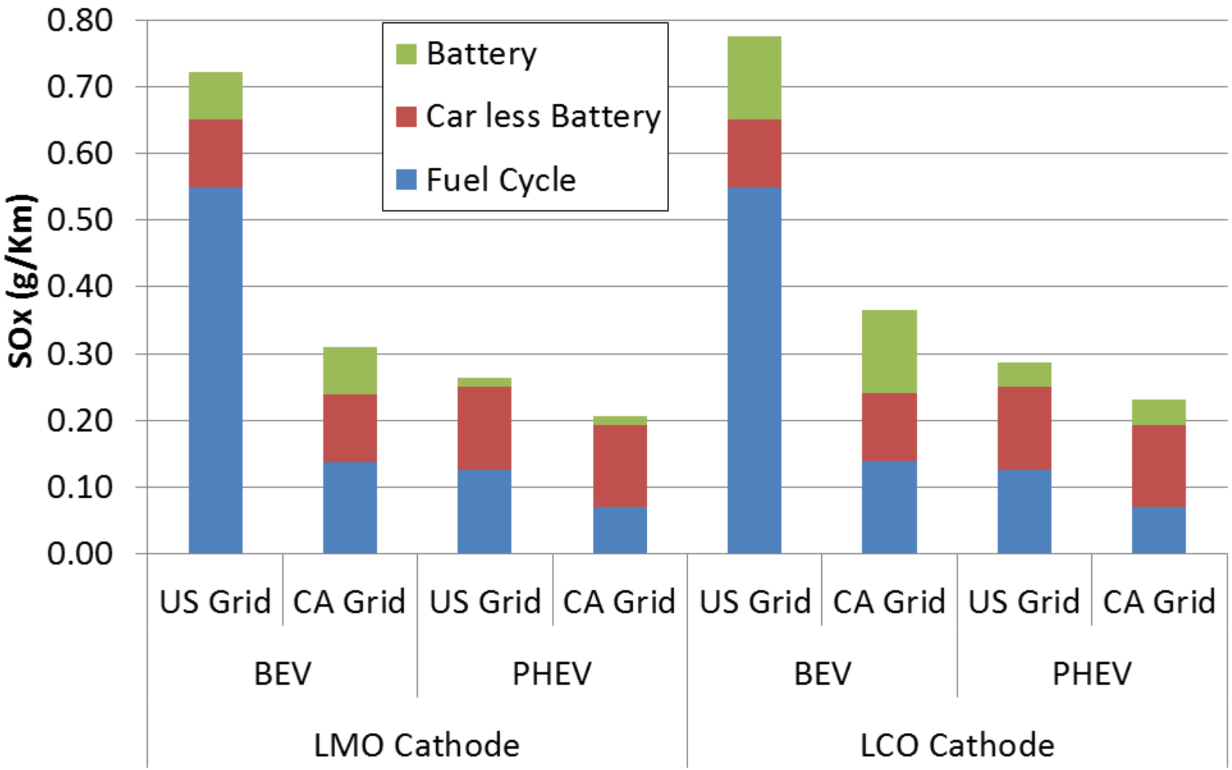
*synthetic graphite

Dunn, JB; Gaines, L; Sullivan, J; Wang, MQ," The Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries, *Env Sci Tech* 46: 12704-12710 ***(2012)***

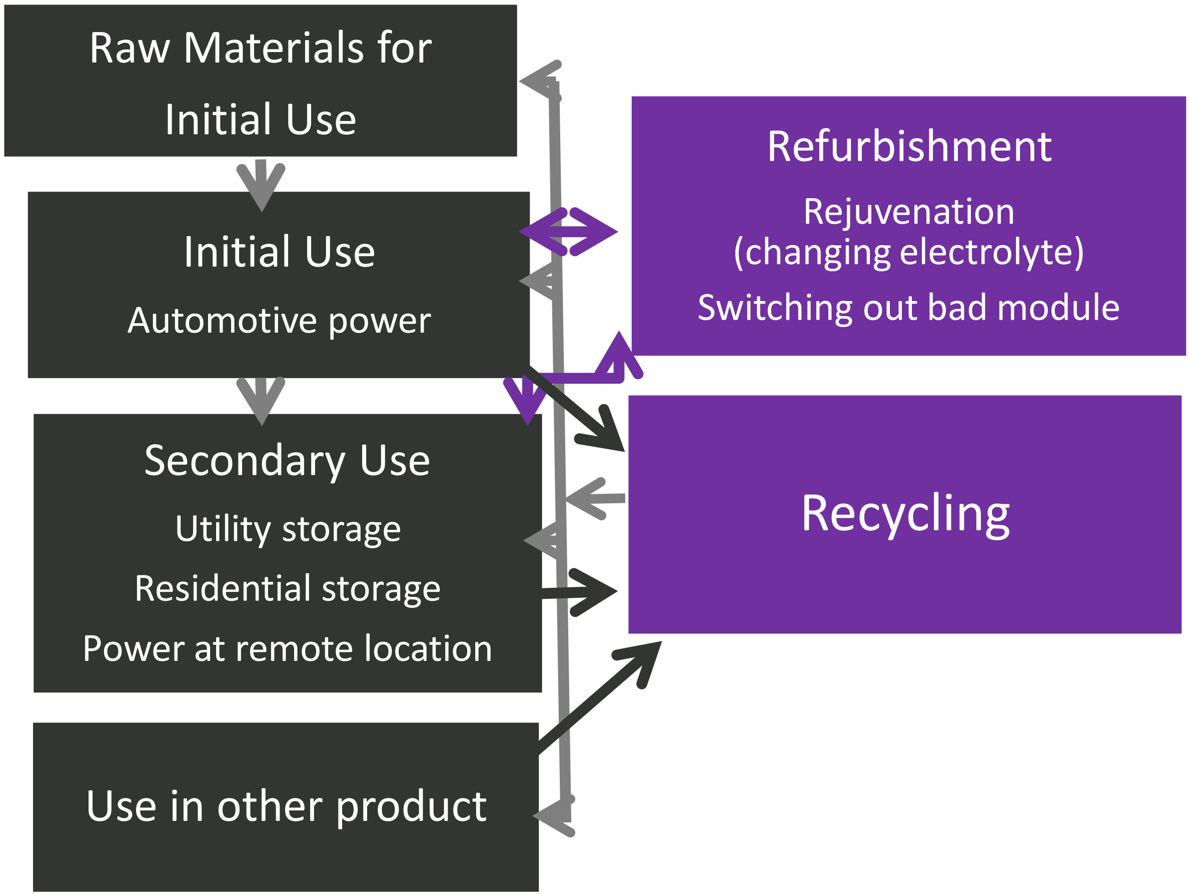
Batteries are small contributors to life-cycle energy use and CO_2 emissions



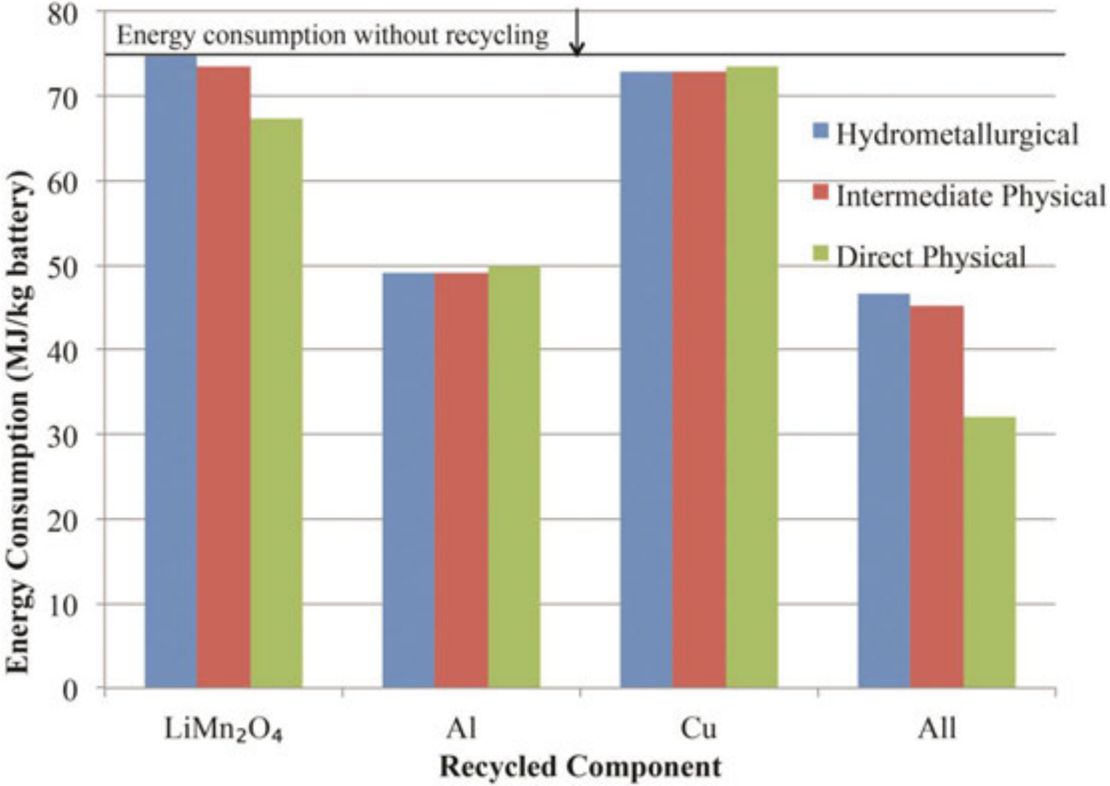
But make significant contributions to life-cycle SO_x emissions,
especially if cathode contains cobalt or nickel



Materials could get used multiple times before recycling



Recycling multiple materials maximizes energy savings and emission reductions



Recycling enables known Li reserves to meet world demand to 2050, even under high demand scenario

	Cumulative Demand to 2050 (Contained Lithium, 1000 Metric Tons)
Large batteries, no recycling	6,474
Smaller batteries, no recycling	2,791
Smaller batteries, recycling	1,981
	Reserve Estimates
USGS Reserves*	13,000
USGS World Resource*	29,000
Other Reserve Estimates	30,000+

*Revised January 2011: http://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2011-lithi.pdf

Without recycling, cobalt use in U.S. alone could impact reserves

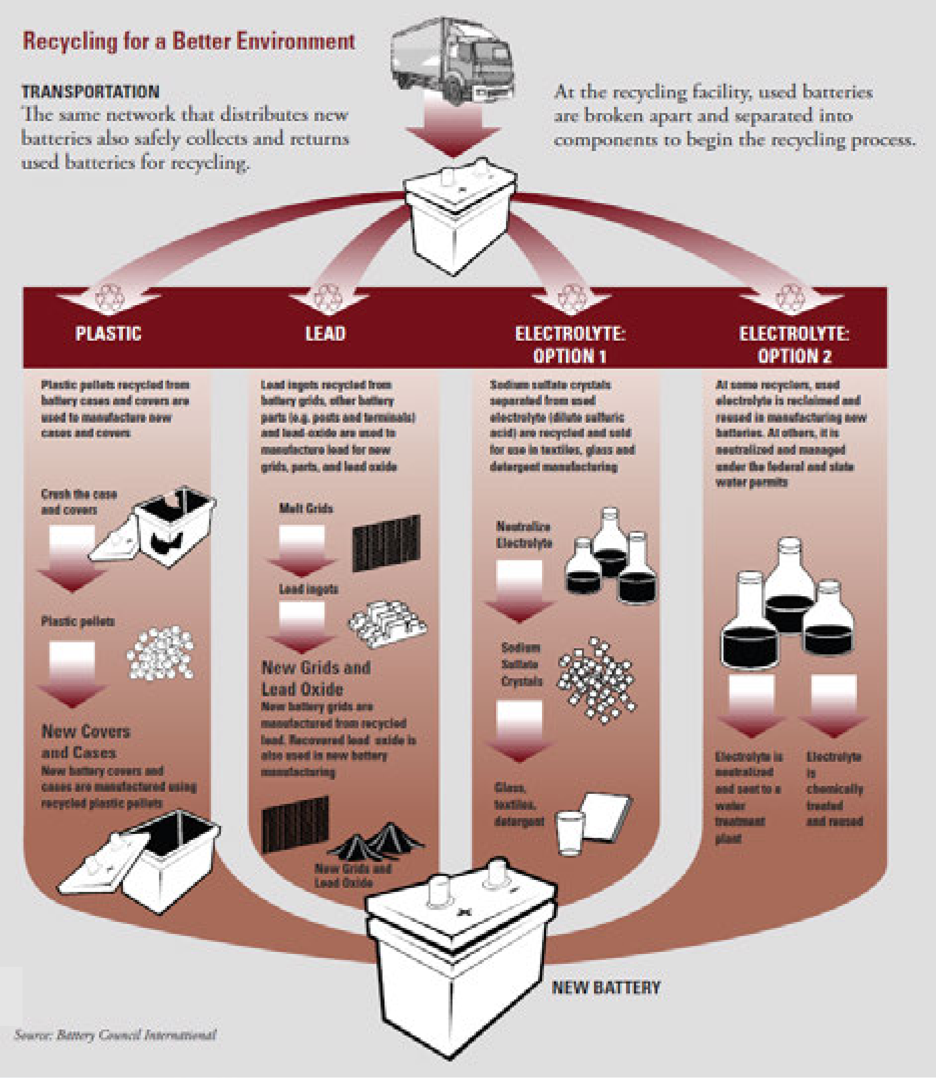
Material	Availability (Million Tons)	Cumulative Demand	Percent Demanded	Basis
Co	13	1.1	9	World reserve base
Ni	150	6	4	World reserve base
Al	42.7	0.2	0.5	US capacity
Iron/steel	1320	4	0.3	US production
P	50,000	2.3	~0	US phosphate rock production
Mn	5200	6.1	0.12	World reserve base
Ti	5000	7.4	0.15	World reserve base

Lead-acid battery recycling can serve as a model

- **~98% of U.S. Pb-acid batteries are collected and recycled**
  - Dealers are required to collect when new ones purchased
  - They are paid to return them
  - Export is averted (but not prevented)
- **Batteries are returned to manufacturer via back-haul**
- **Transport and processing are regulated to protect people and the environment**
  - Recycling avoids sulfur emissions from virgin lead production
  - Lead emissions are tightly regulated
- **The product is standardized and accepted in the marketplace**

Why does the Pb-acid system work so well?

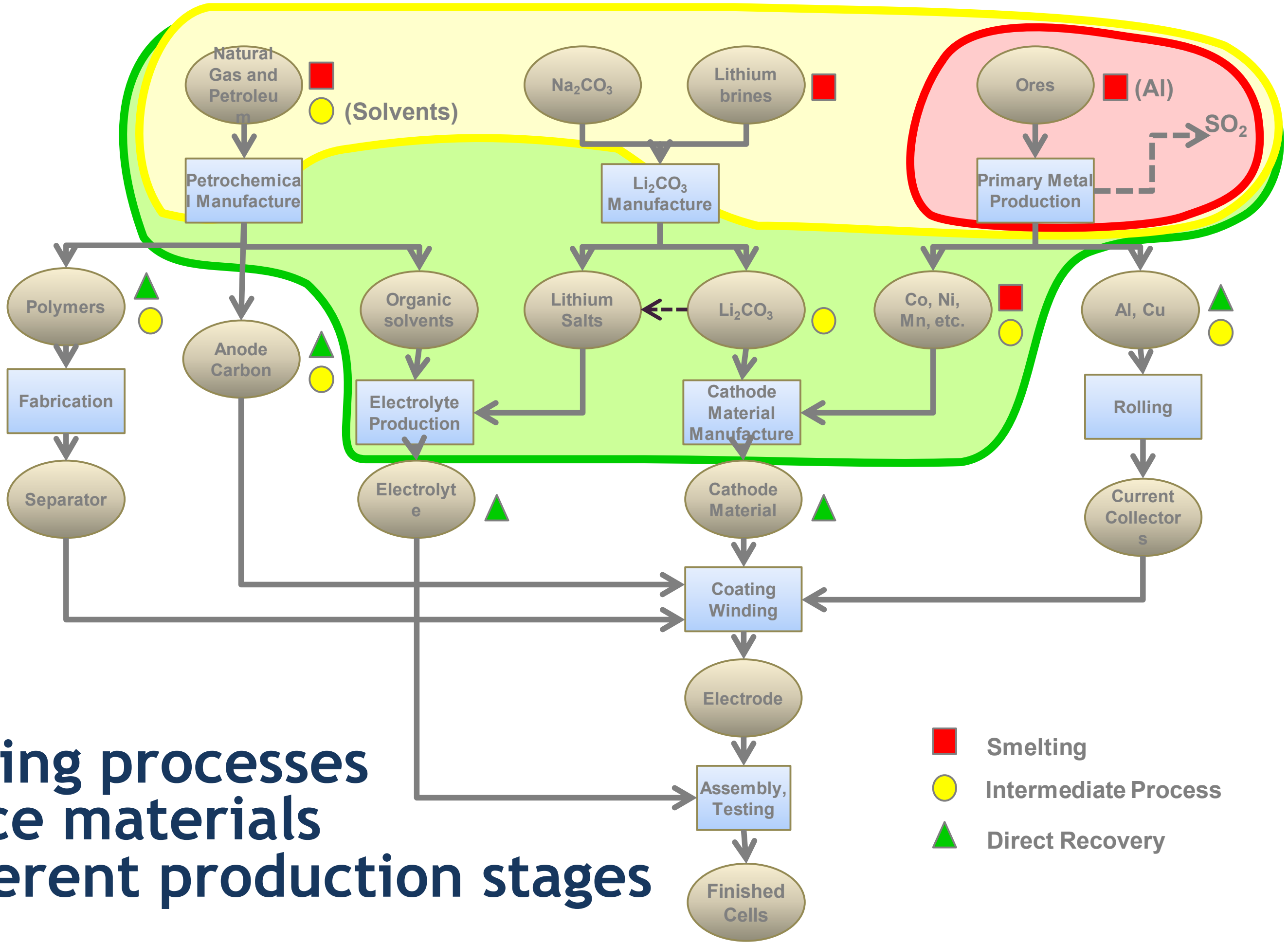
- It’s profitable
- It’s illegal to dispose of the batteries
- There’s a standard format
- The design is simple
- There’s a single chemistry
- The recycling process is simple



Courtesy of Battery Council International

What about nickel-metal hydride?

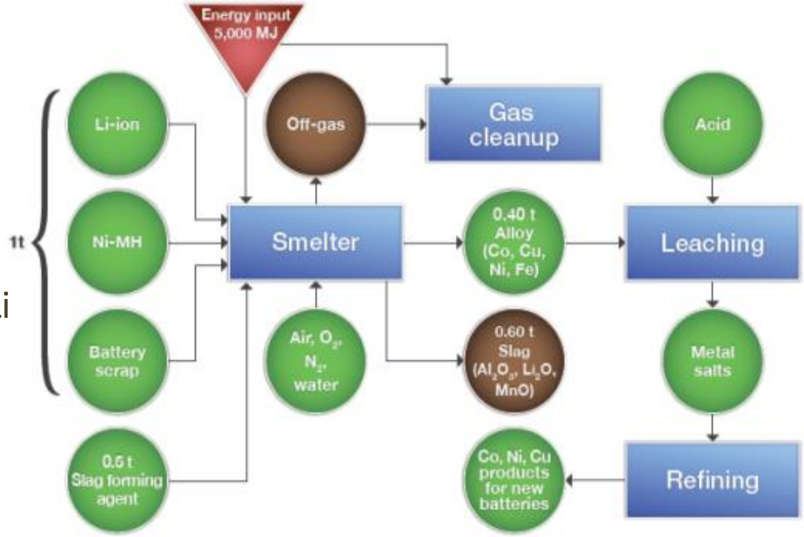
- **Cell chemistry very similar across manufacturers**
  - Cell and pack configurations vary considerably
- **Established recycling method recovers ferronickel for use in stainless steel**
  - Rare earths (RE) report to slag, used as road aggregate
- **Chinese export restrictions are incentive to recover RE**
- **Several projects underway to recycle Ni-MH**
  - Umicore recovers Ni and has agreement with Solvay to recover RE from slag
  - Retriev Technologies has plant under construction in Ohio
  - Honda has agreement with Japan Metals and Chemicals
- **So they're pretty much on track for successful recycling**



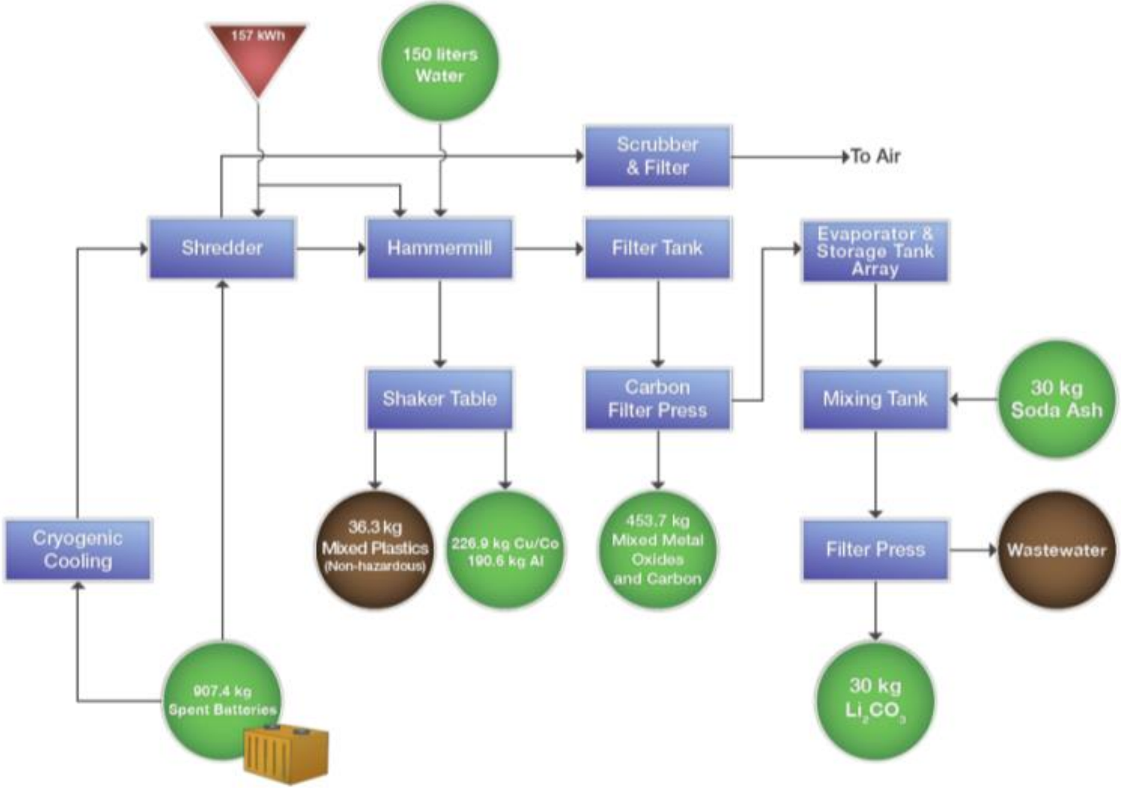
Recycling processes displace materials at different production stages

Smelting processes avoid some metal ore processing

- **These can take just about any input, high volume**
- **High-temperature required**
  - Organics are burned as reductant and for process energy
- **Valuable metals (Co, Ni, Cu) are recovered and sent to refining**
  - Suitable for any use
  - 70% of cobalt production energy saved; sulfur emissions avoided
  - Fabrication still needed
  - Less Co → less value
- **Volatiles burned at high-T**
- **Li, Al go to slag**
  - Recovery from slag would have high impacts
  - Smelter chemistry could be altered to recover Li



Lithium carbonate and metals can be recovered in the current Toxco process



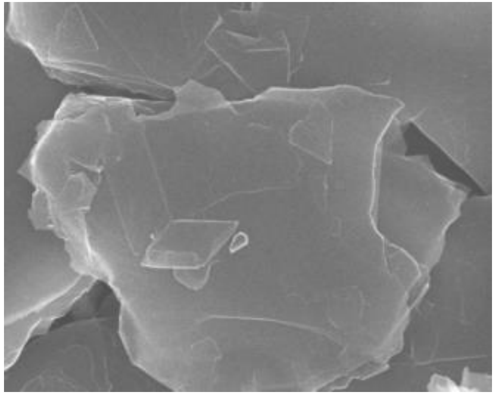
Recovery of battery-grade materials improves economics

- **Direct Recovery requires as uniform feed as possible**
- **Components are separated to retain valuable material structure**
  - Costs lower than virgin materials
  - Purify/reactivate components if necessary for new batteries
  - Has been demonstrated with several cathodes
- **Low-temperature process, low energy requirement and emissions**
- **Does not require large volume; could process prompt scrap**

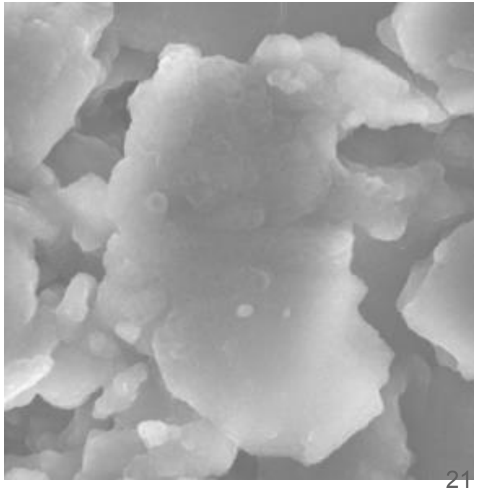
Cathode	Price of Constituents ($/lb)	Price of Cathode ($/lb)
$LiCoO_2$	8.30	12–16
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	4.90	10–13
$LiMnO_2$	1.70	4.50
$LiFePO_4$	0.70	9

Active materials may be degraded after use

- Quality and performance must be verified
- Treatment to upgrade could be developed
- Material may be suited for lower-performance uses
- Number of re-uses might be limited
  for some materials
- Material may be obsolete when recovered



Graphite:
New and after 50% power fade



Recycling processes differ in important ways

	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni, Cu (Li and Al to slag)	Metals or salts, Li_2CO_3 or LiOH	Cathode, anode, electrolyte, metals
Feed requirements	None	Separation desirable	Single chemistry required
Comments	New chemistries yield reduced product value	New chemistries yield reduced product value	Recovers potentially high-value materials; Could implement on home scrap

Making lithium-ion recycling work involves challenges

- **There are many cell and pack sizes, configurations, and vehicle placements**
- **Complex packs include electronics and thermal control systems**
- **There are no regulations, so restrictive ones could be imposed**
- **The technology is still changing**
- **There is no standard chemistry**
- **Many of the materials have low market value**
  - Mixing chemistries may reduce recycled product value
- **Long-term performance of some recycled materials is not proven**
  - Battery makers may be reluctant to purchase recovered compounds

However, there are many positive factors

- **Packs are large and recognizable**
  - Will be labeled
  - Manufacturers could get their own materials back
- **If they last entire vehicle life, they will all end up at scrapyard**
  - Could be collected from utility after 2nd use
- **Housing, circuitry may actually add to value**
- **Recovery of component materials intact could add value**
- **We’ve got 10 years to work it out!**

Design for recycling can reduce recycling costs

- **Include labels or other distinguishing features**
- **Use a minimum number of different materials**
- **Standardize formats and materials**
- **Avoid bad-actor materials (cadmium, arsenic, mercury, halogens)**
- **Enable easy separation of parts**
  - Design separable cooling system
  - Use reversible joining (nuts and bolts instead of welds)
  - Avoid potting compounds

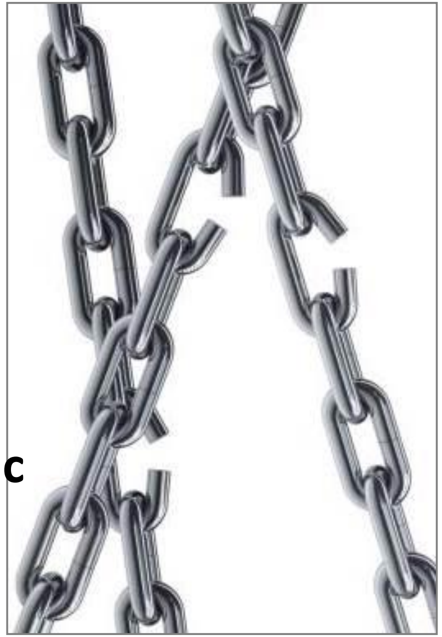
What is needed to make Li-ion recycling viable?

- **Separation technology to enable processing uniform streams**
- **Viable recycling processes for each chemistry, or**
- **Technology for producing valuable product from mixed stream**
  - Could imagine separating material after processing
- **Process flexibility or**
- **Convergence of battery materials and designs**
- **Assurance that regulations will not impede recycling**

Courtesy of Kinsbursky Bros.

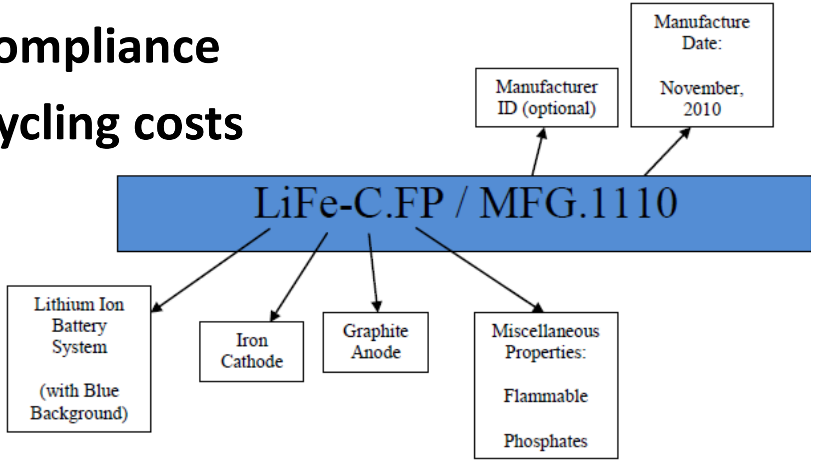
The model system has encountered a problem

- **There have been explosions at secondary lead smelters**
- **The cause is look-alike Li-ion batteries in feed**
- **Mixed in delivered pallets by accident or on purpose**
  - Suppliers paid for Pb-acid, must pay to leave Li-ion
- **Large volumes of material on rapidly-moving conveyors**
- **Lead batteries in Li-ion stream could also be problematic**



Segregation methods for large batteries will help

- **Optimum separation point in recycling process chain is unclear**
  - But rescreening might still be necessary
- **Various labeling technologies could help… eventually**
  - Bar code
  - RFID chips
  - Paint color or type (*e.g.,* visible under black light)
- **Incentives and penalties might enhance compliance**
- **Careful separation is likely to increase recycling costs**



SAE Battery Recycling Committee is addressing this issue

- **Committee Mission: To coordinate and integrate battery recycling issues into the overall strategy of electrification and hybridization of the transportation economy**
- **Diverse group has members from auto companies, battery makers, material suppliers, and recyclers**
  - Coordinates with USABC, USCAR Vehicle Recycling Partnership, USEPA Battery Recycling Lifecycle Project, Industry Groups ABR/BCI, PRBA/RECHARGE, ILA, EUROBAT, and SAE Transportation Committee
  - Contacts are Patricia Ebejer [pebejer@sae.org] or Tim Ellis [Tellis@RSRCorp.com]
- **Already addressed labeling to enable identification prior to recycling**
  - Published document J2984 – Identification of Transportation Battery Systems for Recycling Recommended Practice
- **Preparing document J3071 – Automotive Battery Recycling Identification and Cross-Contamination Prevention – Recommended Practice**
  - **Input welcomed!**

Thank you!

- **Sponsored by USDOE Office of Vehicle Technologies**
- **Contact me: lgaines@anl.gov**

http://www.transportation.anl.gov/technology_analysis/battery_recycling.html